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Earthquakes, Quaternary Faults, and Seismic Hazard in California

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Data describing the locations, slip rates, and lengths of Quaternary faults are the primary basis in this work for constructing maps that characterize seismic hazard in California. The expected seismic moment M_0^e and the strength of ground shaking resulting from the entire rupture of each mapped fault (or fault segment) are estimated using empirical relations between seismic moment M_0, rupture length, source to site distance, and strong ground motions. Assuming a fault model whereby the repeat time T of earthquakes on each fault equals $M_0^e/\dot{M}_0^g$ (where the moment rate $\dot{M}_0^g$ is proportional to fault slip rate), it is observed that the moment-frequency distribution of earthquakes predicted from the geologic data agrees well with the distribution determined from a 150-year historical record. The agreement is consistent with the argument that the geologic record of Quaternary fault offsets contains information sufficient to predict the average spatial and size distribution of earthquakes through time in California. The estimates of T for each fault are the foundation for constructing maps that depict the average return period of $\geqslant 0.1g$ peak horizontal ground accelerations, and the horizontal components of peak acceleration, peak velocity, and the pseudovelocity response (at 1-period and 5% damping) expected to occur at the level of 0.1 probability during a 50-year period of time. A map is also formulated to show the probability that $\geqslant 0.1g$ horizontal ground accelerations will occur during the next 50 years. The maps serve to illustrate the potential value of Quaternary fault studies for assessing seismic hazard. Interpretation of available slip rates indicates that the largest and most frequent occurrence of potentially destructive strong ground motions are associated principally with the San Andreas, San Jacinto, Calaveras, Hayward, and Ventura Basin fault zones. Other regions of similarly high hazard may yet remain unrecognized. This inadequacy results primarily from an incomplete data set. Numerous faults, for example, are mapped along the coastal region of northern California and within the Modoc Plateau, but relatively few studies relating to fault slip rate are reported. A similar problem exists for other stretches of coastal California where marine reflection studies provide evidence of active faulting offshore yet yield little or no information of fault slip rate. Geological and geophysical field studies can work to remove these deficiencies. A concerted effort to locate and define rates of activity on all faults in California is the most promising means to further quantify present levels of seismic hazard in California.

INTRODUCTION

The causal relation between earthquakes and faulting was well described some 100 years ago by *Gilbert* [1884] during his discussion of earthquakes in the Great Basin. *Koto* [1893] independently noted the same causality during his study of the great 1891 Nobi earthquake of Japan. Later field investigations of the great 1906 California earthquake by *Lawson* [1908] and his colleagues removed most remaining doubt of the close connection between faulting and earthquakes. Moreover, *Reid's* [1910] geodetic study of that same earthquake provided a physical model to explain the occurrence of earthquake faulting, the now well-known concept of elastic rebound. These observations prompted *Willis* [1923] to suggest as early as 1923 that a fault map of California was a good indicator to the sites of future earthquakes. Since these studies, knowledge of the mechanics of earthquake faulting has continued to grow, moderate to large earthquakes have consistently been observed to rupture along mapped faults, and faults that break Quaternary deposits are now commonly accepted as sources of seismic hazard. The purpose of this work is to use our current understanding of fault mechanics to interpret data that describe the average rates of offset across Quaternary faults, with an aim toward developing maps that depict long-term seismic hazard in California: specifically, the average size and spatial distribution of earthquakes through time and, of more practical consequence, the expected occurrence rate of the resulting strong ground motions.

The motivation for this study resides in the uncertainties inherent to more conventional forms of seismic hazard analysis, which are based primarily on earthquake frequency statistics obtained from historical catalogues of seismicity. The uncertainty in such analyses is large when the historical record is too short to define secular rates of seismicity, which is the usual case, particularly when relatively small regions are considered. In contrast to historical data, the geologic record of Quaternary fault offsets contains information on the occurrence of earthquakes through periods of time many orders longer than the average repeat time of large earthquakes on individual faults and orders of magnitude greater than periods covered by historical records. Observations such as these have recently led a number of investigators to argue that geologic information of fault offset rates may be used to reduce uncertainties associated with estimates of long-term seismicity and, in turn, seismic hazard [e.g., *Allen*, 1975; *Anderson*, 1979; *Molnar*, 1979]. The following exercise is thus an attempt at placing this idea into a quantitative framework for analysis of seismic hazard in California. The approach I will take follows that developed in a recent study of seismic hazard in Japan [*Wesnousky et al.*, 1984]. The underlying premise of that work was that moderate to large earthquakes occur on mappable Quaternary faults and that the occurrence rate of

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TABLE A1. Quaternary Faults

Fault	Location* lat	Location* lon	S†	L‡	M§	C#	Slip Rate§ mm/yr Mn	Slip Rate§ mm/yr Mx	Slip Rate§ mm/yr Pr	T**	D††	A**	Reference‡‡
													Peninsular Ranges and Salton Trough
Chino	34.0	117.7	rr?	28	6.8	B	0.0	0.2	0.1		v	q	*Yerkes et al* [1965]b *Heath et al* [1982]c
Elsinore A (Whittier)	33.8	117.7	rl	74	7.3	A	0.6	9.0	4.0	730	h	h	see segment D
Elsinore B	33.5	117.2	rl	51	7.1	A	0.6	9.0	4.0	553	h	h	see segment D
Elsinore C	33.2	116.7	rl	64	7.2	A	0.6	9.0	4.0	651	h	h	see segment D
Elsinore D	32.8	116.2	rl	69	7.2	A	0.6	9.0	4.0	694	h	h	see appendix and *Crowell and Sylvester* [1979]b *Lamar et al.* [1973]a *Lowman* [1980]b *Sage* [1973]a *Weber* [1977]a *Pinault and Rockwell* [1984]
Imperial-Brawley (1979 rupture)	32.8	115.5	rv?	40	6.7	AA	20.0			32††	t	h	see the appendix and *Sharp* [1980]c *Sharp* [1982]c *Sharp et al* [1982]c *Sharp and Lienkaemper* [1982]c *Clark et al* [1984]
Imperial-Brawley (1940 rupture)	32.7	115.4	rv	69	6.9	A		8.6		700††	h	h	see 1979 segment
La Nacion	32.7	117.1		19	6.6	C							*Jennings* [1975]
Newport - Inglewood A	33.7	118 1	rv?	34	6.9	A	0.1	6.0	1.0	1650	v	h	see segment B
Newport - Inglewood B	33.9	118.3	rv?	28	6 8	A	0.1	6.0	1.0	1454	v	h	see the appendix and *Castle* [1960]c *Castle and Yerkes* [1976]c *California Department Water Resources* [1968]c *Poland and Piper* [1956]c *Wright et al* [1973]a *Yeats* [1973]b
Palos Verdes	33.8	118.3	rr?	45	7.0	A	0.02	0.7	0.7	2905	v	h	*Yerkes et al.* [1965]a,b *Darrow and Fisher* [1983]c
Rose Canyon	32.8	117.2	rr?	50	7.1	A	0 0	2.2	1.5	1458	t	q	*Artim and Streiff* [1981] *Ferrand et al* [1981] *Kennedy* [1975a]b *Kern* [1977]c *Moore and Kennedy* [1975]c
San Jacinto Fault Zone (reference summary)													*Sharp* [1981] *Bartholomew* [1970]b *Clark et al.* [1972] *Savage and Prescott* [1976] *King and Savage* [1983] *Sharp* [1967] *Thatcher et al.* [1975] *Brune* [1968]
San Jacinto (Lytle Creek-Glenn Helen - Claremont)	34.5	117.2	rl	78	7.0	AA			10.0	107	h	q	see the appendix
San Jacinto (Hot Springs)	33.7	116.8		29	6.8	C							see the appendix
San Jacinto (Thomas Mountain)	33.6	116.6		15	6.5	C							see the appendix
San Jacinto (Casa Loma - Clark)	33.5	116.6	rl	100	7.1	AA	8.0		10.0	128	h	q	see the appendix
San Jacinto (Buck Ridge)	33.5	116.5	rl	35	6 6	A			2 0	294	h	q	see the appendix
San Jacinto (Coyote Creek)	33.3	116 4	rl	38	6.6	A			2.0	314	h	q	see the appendix
San Jacinto (Borrego Mountain)	33.1	116.1	rl	30	6.5	A	1 6	5.0	2.0	150††	h	h	see the appendix
San Jacinto (Superstition Mountain)	32.9	115 8	rl	26	6.4	A			1.0	468	h	q	see the appendix
San Jacinto (Superstition Hills)	33.0	115 8	rl	22	6.4	A			1.0	422	h	q	see the appendix

TABLE A1. (continued)

Fault	Location* lat	Location* lon	S†	L‡	M§	C#	Slip Rate δ mm/yr Mn	Slip Rate δ mm/yr Mx	Slip Rate δ mm/yr Pr	T**	D††	A‡‡	Reference§§
							San Andreas						
San Andreas (Shelter Cove to San Juan Bautista)	38.5	122.8	rl	420	7.8	AA	6.9	30.0	12.0	300†‡	h	h	*Hall* [1984]b *Cummings* [1968] *Prescott and Yu* [1986] *Addicott* [1969] *Clark et al.* [1984]
San Andreas (Los Altos to San Juan Bautista)	37.1	121.9	rl	85	7.0	AA			12.0	140†‡	h	h	*Prescott et al. (1981)* *Hall* [1984]b
San Andreas (San Juan Bautista to Bitterwater)	36.6	121.2	rl	86	7.0	AA	10.0	39.0	5.0	228	h	h	see the appendix and *Burford and Harsh* [1980] *Clark et al.* [1984]
San Andreas (Bitterwater to Slack Canyon)	36.2	120.7	rl	51				33.9	0.01				*Burford and Harsh* [1980]
San Andreas (Slack Canyon to Cholame)	35.9	120.4	rl	37	6.6	AA			33.9	28†‡	h	h	*Bakun and McEvilly* [1984]
San Andreas (Slack Canyon to Hwy 58)	35.7	120.2	rl	85	7.0	AA			33.9	140†‡	h	h	*Sieh* [1984] *Sieh and Jahns* [1984]
San Andreas (Slack Canyon to Cajon Pass)	35.2	119.0	rl	337	7.7	AA	5.8	67.0	33.9	345†‡	h	h	*Rust* [1982a,b]c *Sieh* [1984]
San Andreas (Hwy. 166 to Cajon Pass)	34.6	118.4	rl	177	7.4	AA				360†‡		h	*Sieh* [1978a,1984]
San Andreas (Cajon Pass to Salton Sea)	33.9	116.7	rl	210	7.5	AA	10.0	35.0	25.0	170†‡	h	h	*Weldon and Sieh* [1985] *Rasmussen* [1982] *Keller et al* [1982] *K. E. Sieh* (personal communication, *1986)*

* Location of fault. Coordinates mark approximate latitude (°N) and longitude (°W) of fault midpoint.

• Fault name assumed without reference to earlier studies.

† Fault type (e.g., reverse (r), normal (n), right-lateral (rl), left-lateral (ll), right-reverse (rr), left-reverse (lr), right-vertical (rv), left-vertical (rv), right-normal (rn), left-normal (ln)).

‡ Fault length (kilometers).

§ Moment-magnitude M_w of earthquake expected for rupture of entire fault length, estimated with slip rate dependent empirical relations between seismic moment M_o and fault length in Figure 2, and assuming the empirical relation $\log M_o = 1.5M_w + 16.1$ [*Hanks and Kanamori*, 1979].

Slip rate class: AA $\geq$ 10 mm/yr; A $\geq$ 1 mm/yr; B $\geq$ 0.1 mm/yr; C $\geq$ 0.01 mm/yr. Faults are assumed to be class C when no slip rate data are available and assigned a slip rate equal to 0.01 mm/yr for hazard map development.

δ The minimum (Mn) and maximum (Mx) values of slip rate reported by referenced investigators. The preferred (Pr) value of rate, when listed, is used for estimating T. Otherwise, T is estimated with either the minimum, maximum, or average of the minimum and maximum reported rates, depending on which limits are placed on the respective faults

** Repeat time of rupture for each fault estimated with equation (1) unless marked by †‡. Repeat times estimated to be greater than 10,000 years are not listed.

†† The reported slip rate is determined primarily from the horizontal (h), vertical (v), dip-slip (d), or the total (t) component of displacement.

‡‡ Youngest feature used to determine slip rate and/or repeat time along entire fault zone; Holocene (h), Pleistocene (q), Pliocene (p), or Miocene (m). Range of slip rates may reflect rates determined from older offsets as well.

§§ References regarding location, slip rate, and repeat time of each fault. A letter a, b, or c following the reference indicates that values of slip rate listed are those reported by a, *Anderson* [1979], b, *Bird and Rosenstock* [1984]; and c, *Clark et al.* [1984], respectively.

†‡ Based on historical information, trenching studies, or other geological inferences, rather than equation (1). Cases are discussed in the appendix.

Clark fault is about 19 km, whereas total horizontal separation across the Coyote Creek and Buck Ridge faults is about 5-6 km. For the hazard analysis, slip rates of the individual faults are assumed to be approximately proportional to the total separation documented across each fault, though it is recognized that no evidence is reported to document the relative youth of the three faults. The Buck Ridge and Coyote Creek faults are accordingly assigned slip rates of 2.0 mm/yr for the hazard analysis.

The 30-km section of fault that broke during the magnitude 6.8 earthquake in April of 1968 (Table 2) is here referred to as the Borrego Mountain fault (Figure A2). The Borrego Mountain fault is the only major mapped fault strand to continue immediately south of the Clark, Coyote